FOUR-NOZZLE BENCHMARK WIND TUNNEL MODEL USA CODE SOLUTIONS FOR SIMULATION OF MULTIPLE ROCKET BASE FLOW RECIRCULATION AT 145,000 FT ALTITUDE

by

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ABSTRACT

Multiple rocket exhaust plume interactions at high altitudes can produce base flow recirculation with attendant alteration of the base pressure coefficient and increased base heating. A search for a good wind tunnel benchmark problem to check grid clustering technique and turbulence modeling turned up the experiment done at AEDC in 1961 by Goethert and Matz on a 4.25-in. diameter domed missile base model with four rocket nozzles. This wind tunnel model with varied external bleed air flow for the base flow wake produced measured p/p_{ref} at the center of the base as high as 3.3 due to plume flow recirculation back onto the base. At that time in 1961, relatively inexpensive experimentation with air at $\gamma = 1.4$ and nozzle A_e/A^* of 10.6 and $\theta_n = 7.55$ deg with $P_c = 155$ psia simulated a LO_2/LH_2 rocket exhaust plume with $\gamma = 1.20$, A_e/A^* of 78 and P_c about 1,000 psia. An array of base pressure taps on the aft dome gave a clear measurement of the plume recirculation effects at $p_\infty = 4.76$ psfa corresponding to 145,000 ft altitude. Our CFD computations of the flow field with direct comparison of computed-versus-measured base pressure distribution (across the dome) provide detailed information on velocities and particle traces as well eddy viscosity in the base and nozzle region. The solution was obtained using a six-zone mesh with 284,000 grid points for one quadrant taking advantage of symmetry. Results are compared using a zero-equation algebraic and a one-equation pointwise R_t turbulence model (work in progress). Good agreement with the experimental pressure data was obtained with both; and this benchmark showed the importance of: (1) proper grid clustering and (2) proper choice of turbulence modeling for rocket plume problems/recirculation at high altitude.

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FOUR-NOZZLE CLUSTER HIGH ALTITUDE BASE FLOW BENCHMARK

OBJECTIVE

- SHOW THE CAPABILITIES OF THE USA CODE TO SOLVE HIGH-ALTITUDE (> 100,000 FT) MISSILE CLUSTERED-NOZZLE BASE FLOW PROBLEMS AS TO SOLUTION ALGORITHM AND TURBULENCE MODEL (SEPARATE FROM CHEMISTRY OR ENERGY/HEAT TRANSFER SIMULATIONS).

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APPROACH

BENEFITS

- CLASSICAL EXPERIMENT FROM 1961 WITH AIR SIMULATES CLUSTERED LO_2/LH_2 ENGINES
- THIS BENCHMARK ISOLATES ALGORITHM, GRIDDING TECHNIQUE, AND TURBULENCE MODEL ACCURACIES
- EXCELLENT HIGH ALTITUDE EXPANSION TEST FOR THE CODE

NOTE - CHEMISTRY PACKAGE BENCHMARK CONDUCTED AND REPORTED SEPARATELY

AREAS FOR IMPROVEMENT

- ALTHOUGH GROSS FEATURES OF FLOW FIELD ADEQUATELY SIMULATED, AGREEMENT WITH BASE PRESSURE FLOW BETWEEN NOZZLES HAS REMAINING SMALL DISCREPANCY

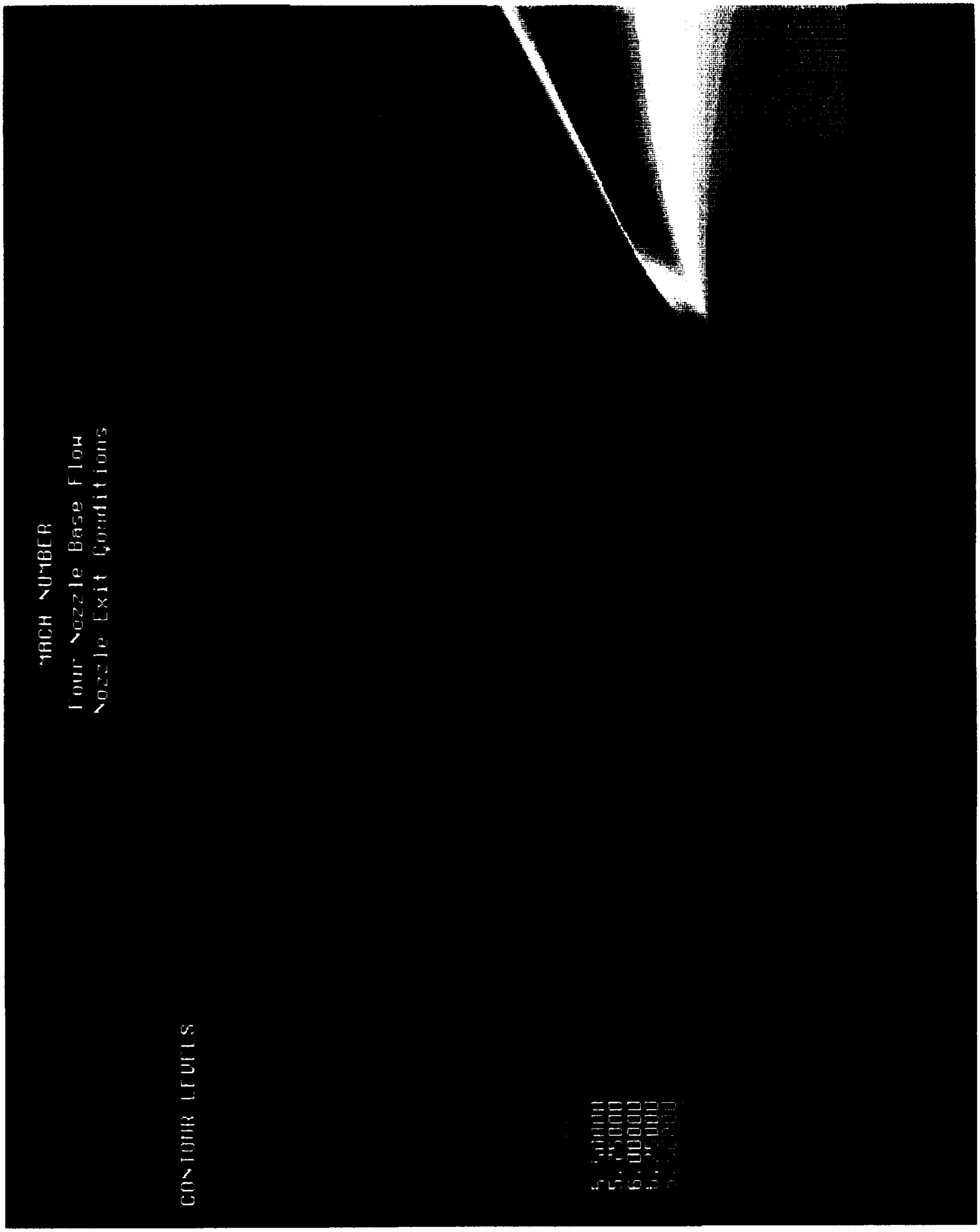
FOUR-NOZZLE CLUSTER HIGH ALTITUDE BASE FLOW BENCHMARK

• *EXPERIMENT DESCRIPTION*

THE CLUSTERED NOZZLE BASE FLOW EXPERIMENTS CONDUCTED IN 1961 BY R. J. MATZ AND D. W. LITTLE AT ARNOLD ENGINEERING DEVELOPMENT CENTER WERE SELECTED AS CFD BENCHMARK CASES FOR HIGH ALTITUDE PLUME INTERACTION EFFECTS. THE SPECIFIC CASE CHOSEN FOR SIMULATION IS DESCRIBED BELOW:

- Ae/At 10.63
- P_∞/Pc 0.000213
- Pc 155 psia
- h 145,000 FT (PRESSURE ALTITUDE)
- HIGH PRESSURE AIR UTILIZED TO SIMULATE PLUMES

THESE CONDITIONS ARE REPRESENTATIVE OF A FULL-SCALE CONFIGURATION WITH A NOZZLE AREA RATIO OF APPROXIMATELY 80 AND AN EXHAUST GAS SPECIFIC HEAT RATIO OF 1.2



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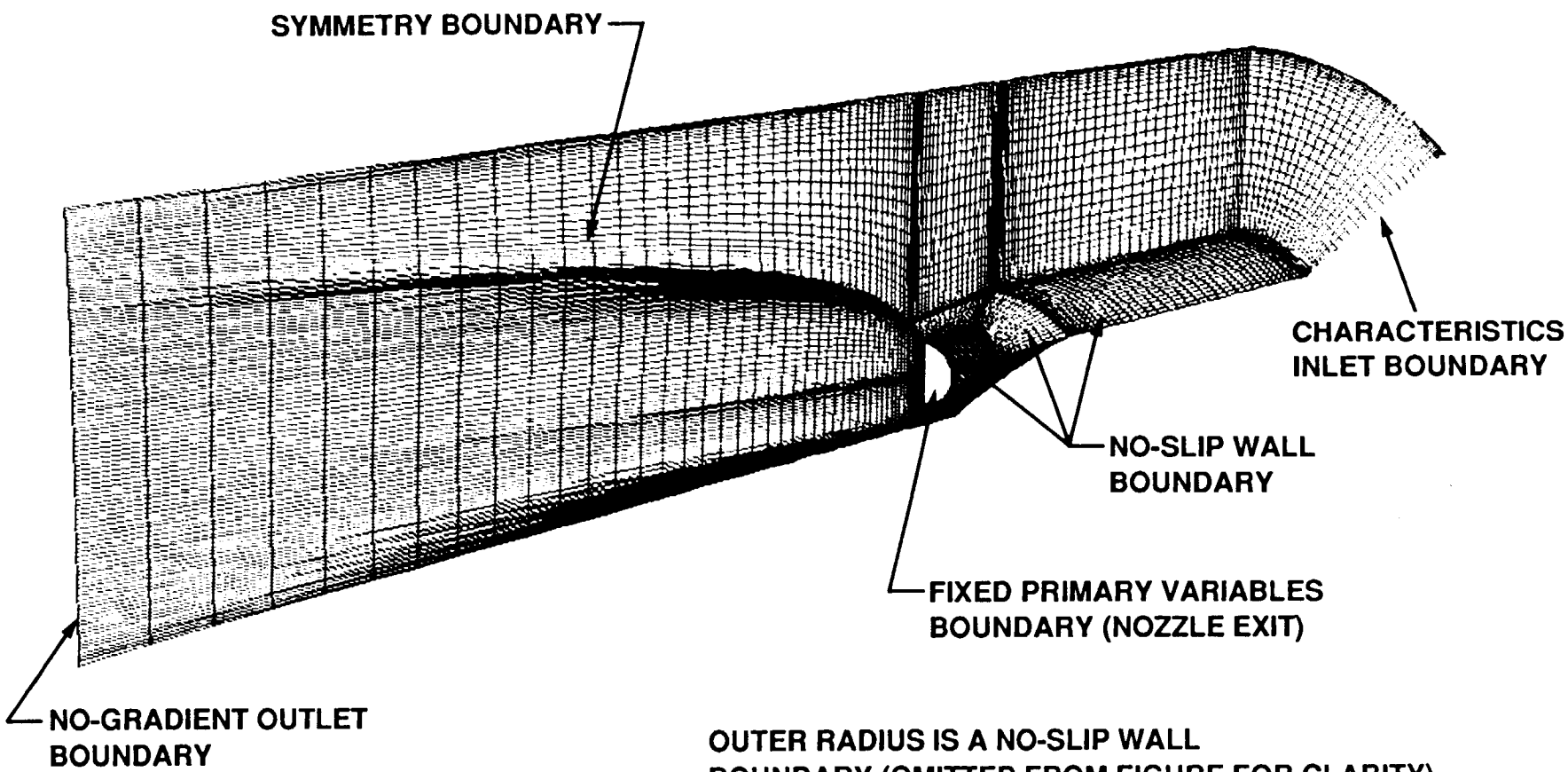
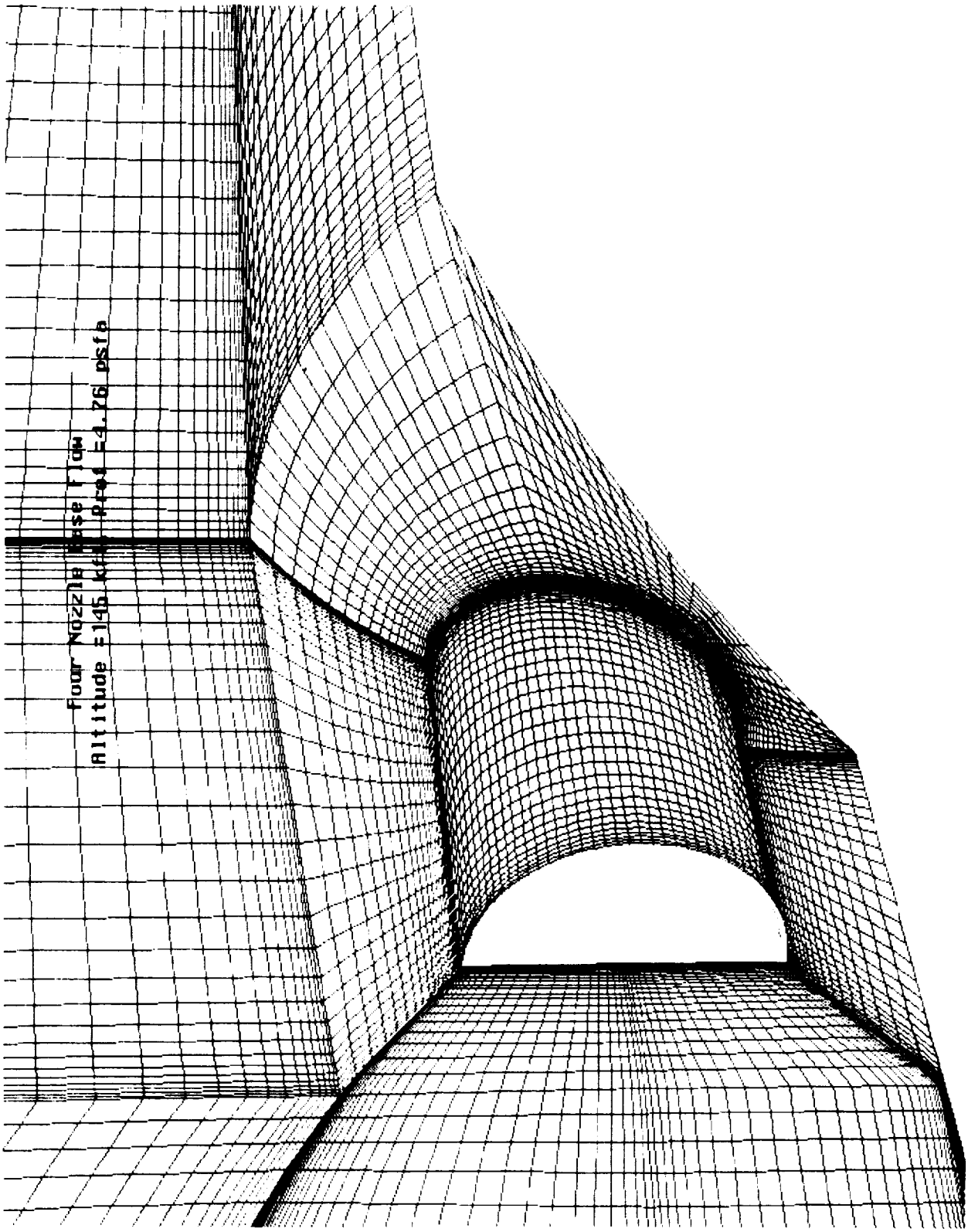
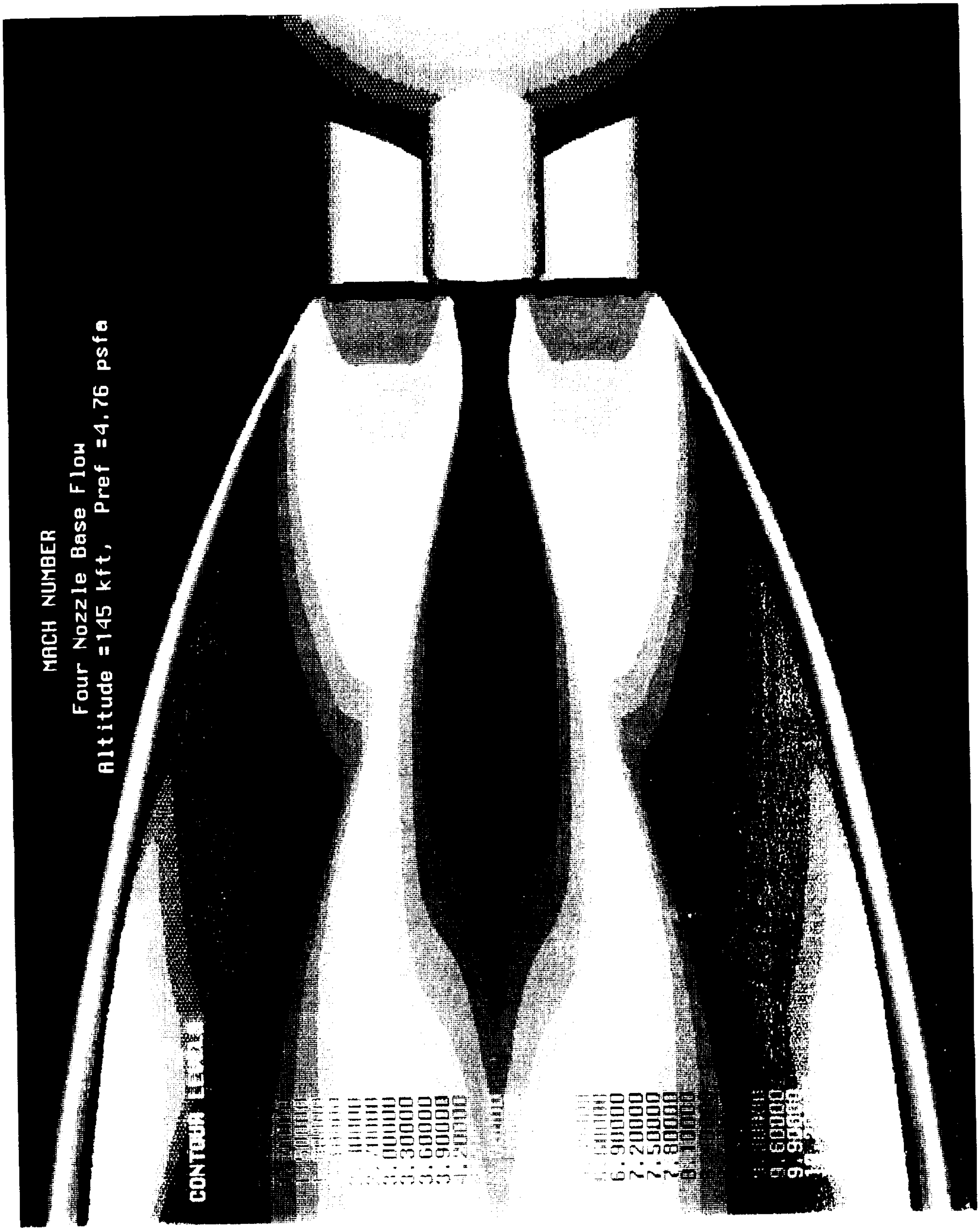
OF POOR QUALITY

FOUR-NOZZLE CLUSTER HIGH ALTITUDE BASE FLOW BENCHMARK



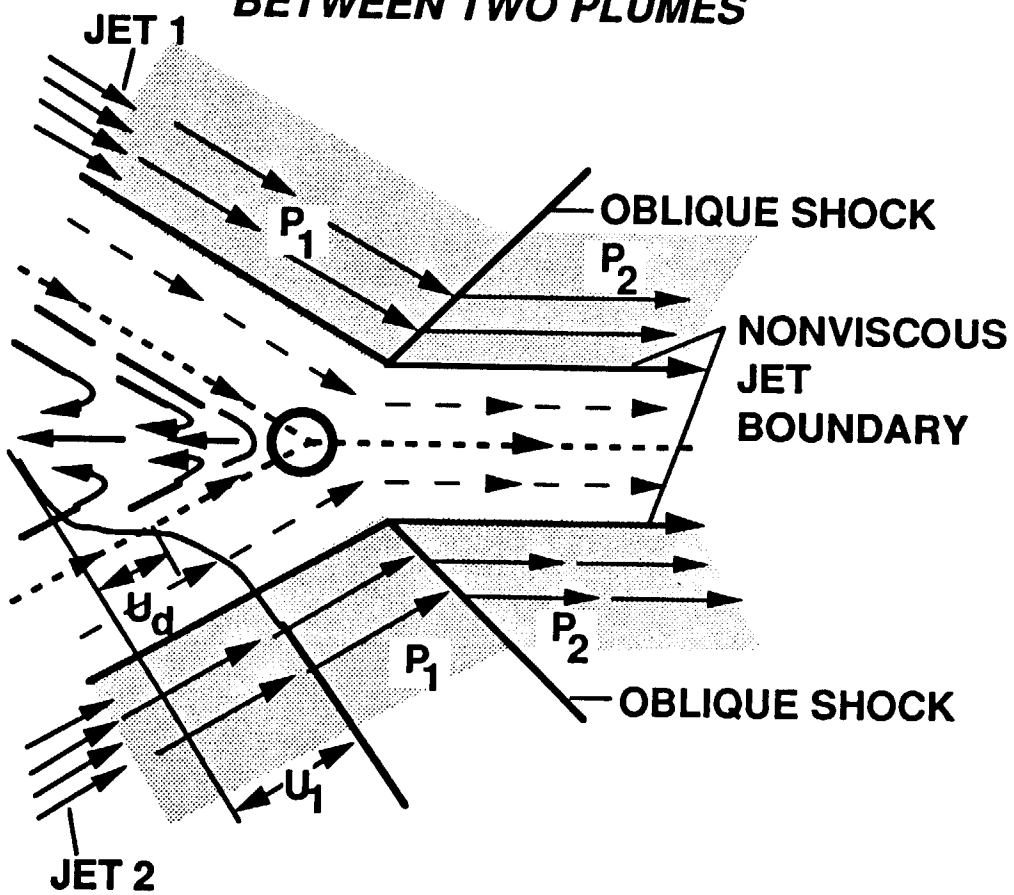
OUTER RADIUS IS A NO-SLIP WALL BOUNDARY (OMITTED FROM FIGURE FOR CLARITY)


Four Nozzle Base Flow
Altitude =145 k
Prod =4.76 psfa



FOUR-NOZZLE CLUSTER HIGH ALTITUDE BASE FLOW BENCHMARK

DISCRIMINATING STREAMLINE FORMED AT THE INTERSECTION BETWEEN TWO PLUMES

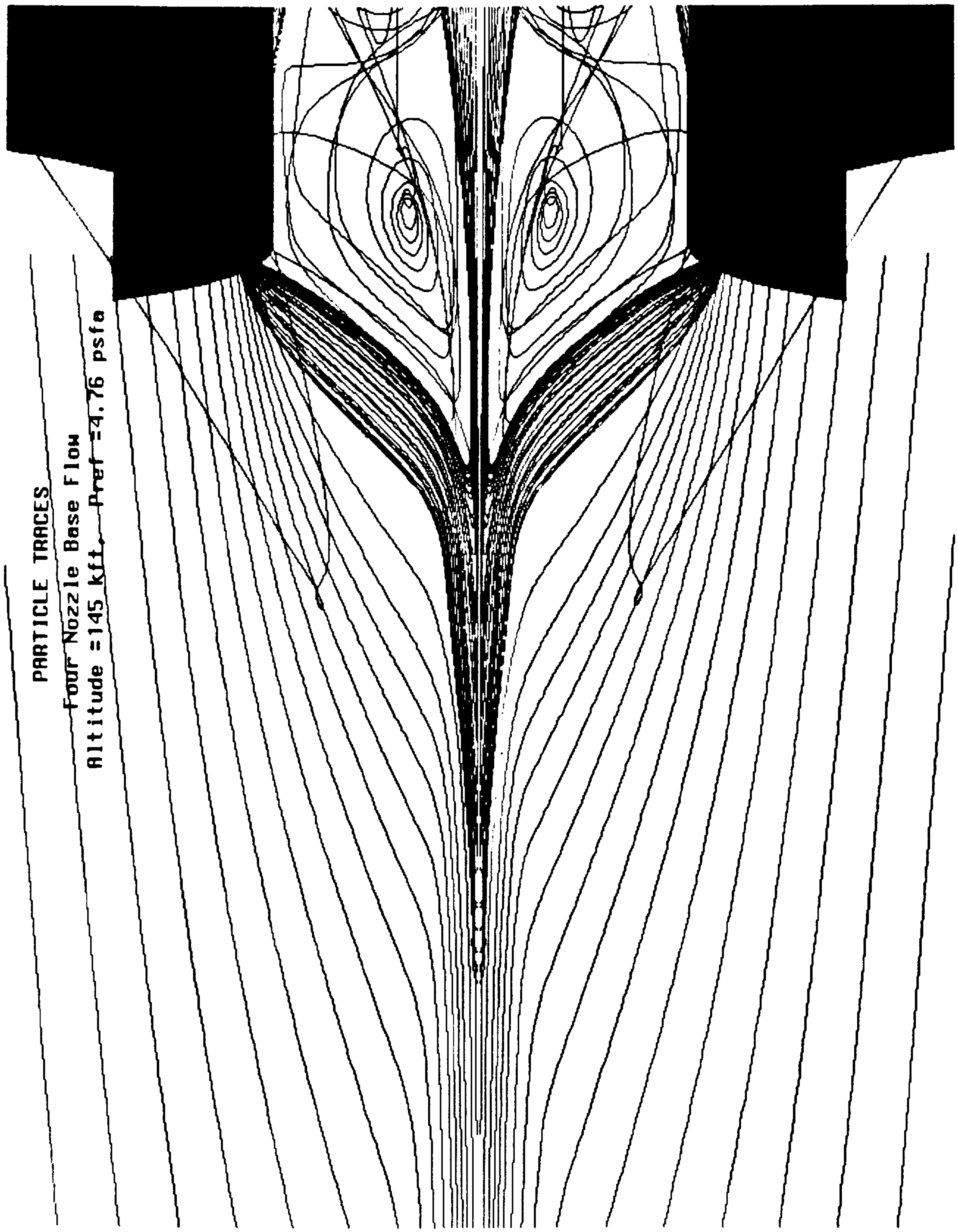


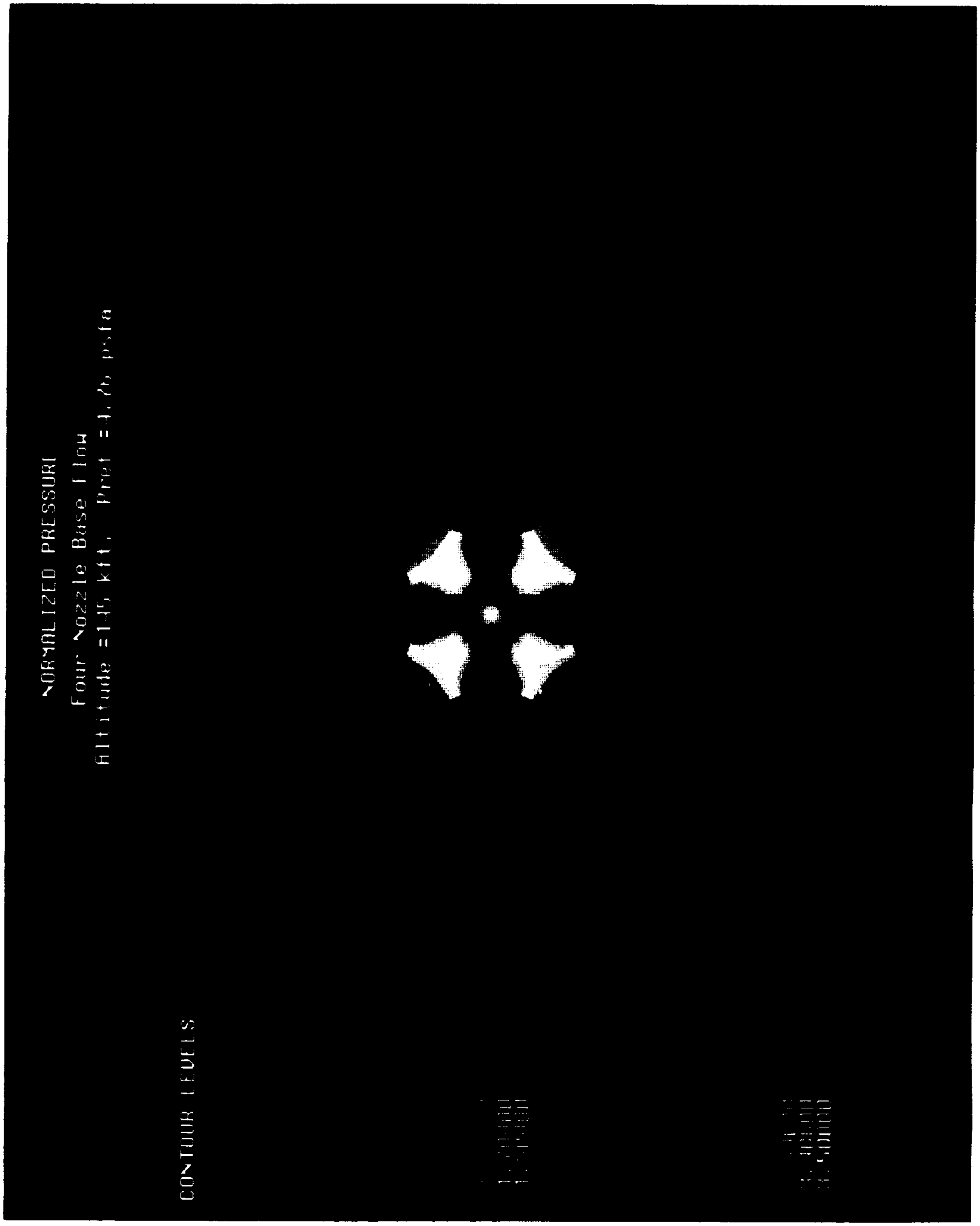
DISCRIMINATING STREAMLINE:

VELOCITY = U_d
MACH NUMBER = M_d

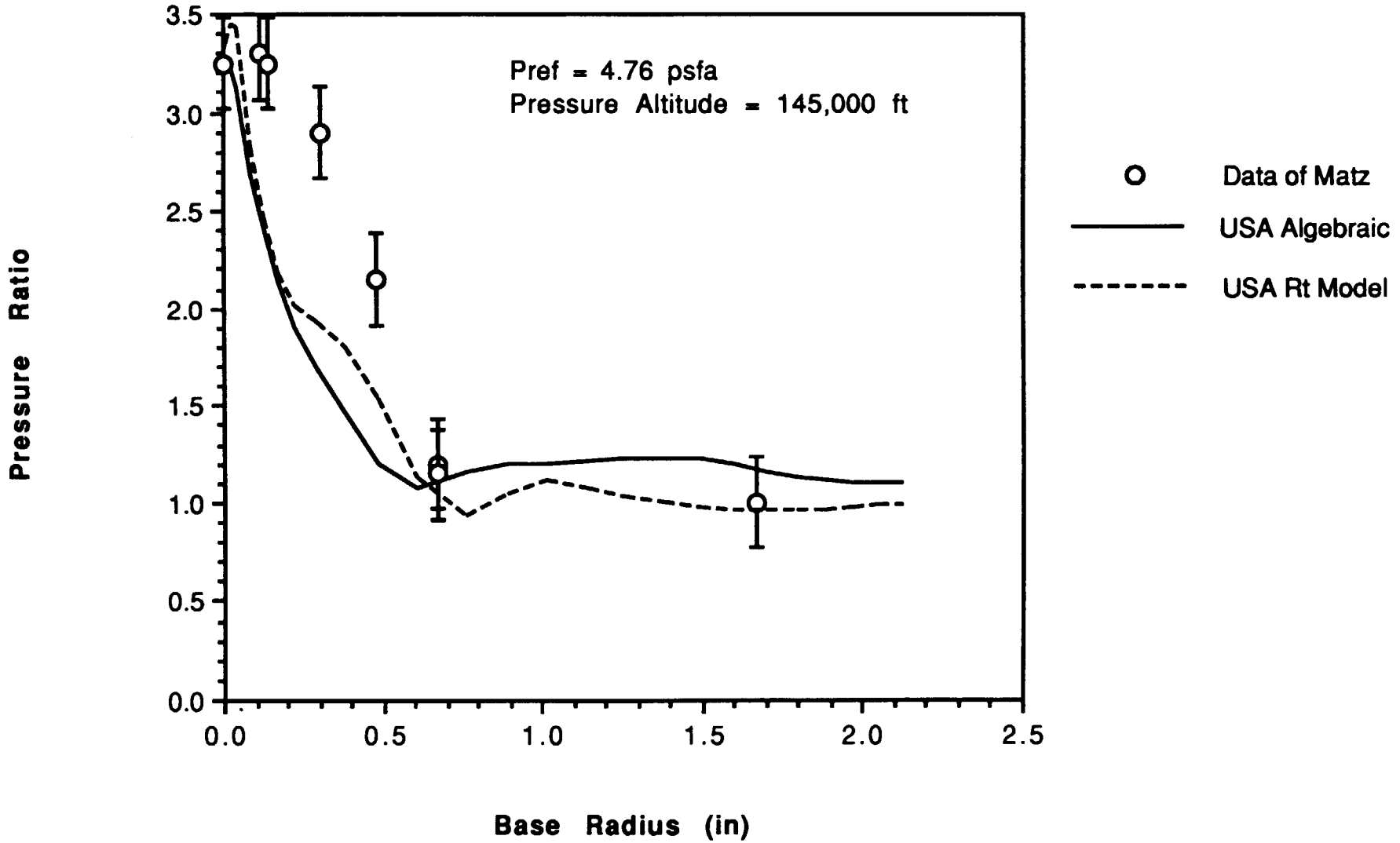
NORMAL SHOCK FOR M_d

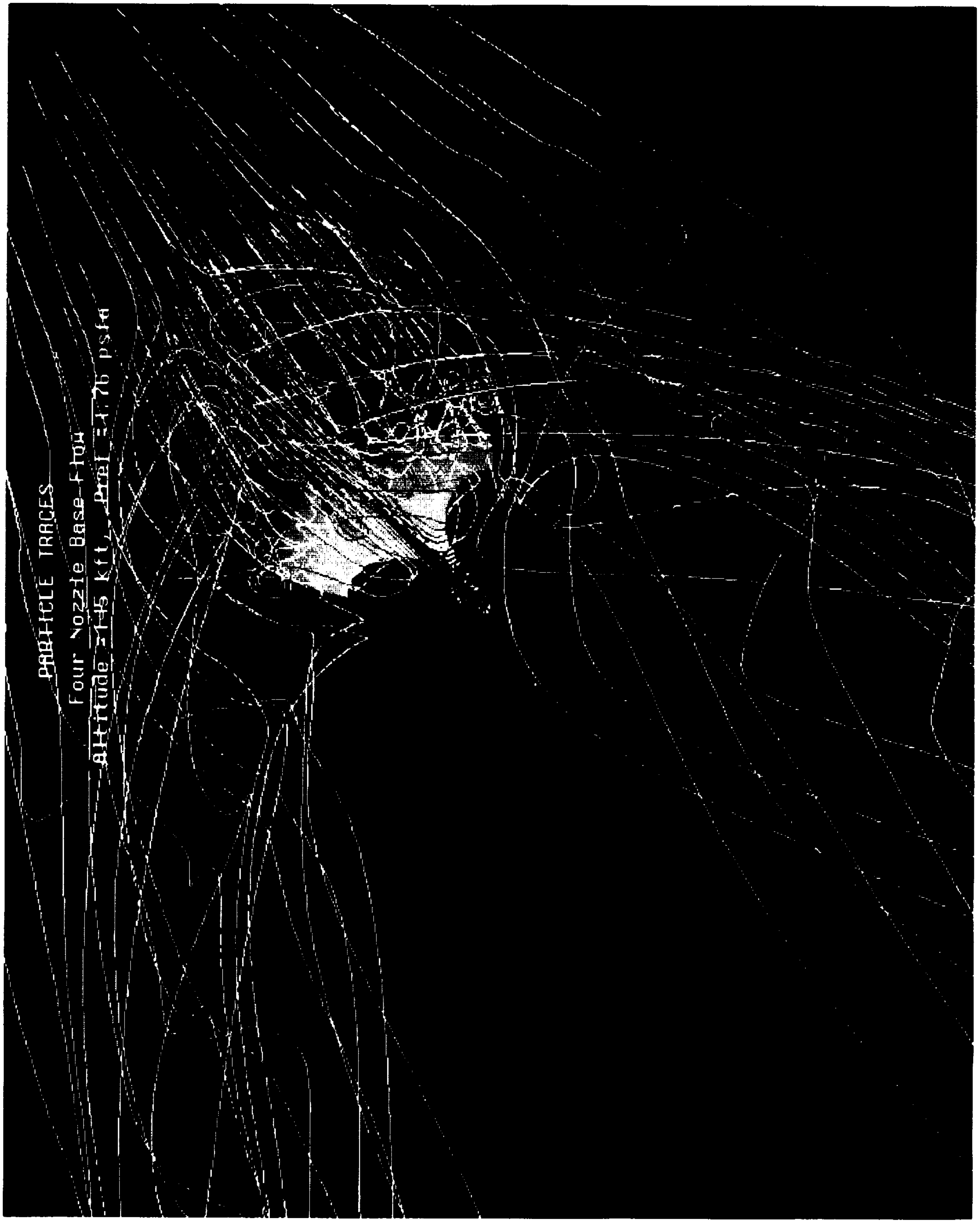
$$P_s = P'_{ts}(M_d)$$

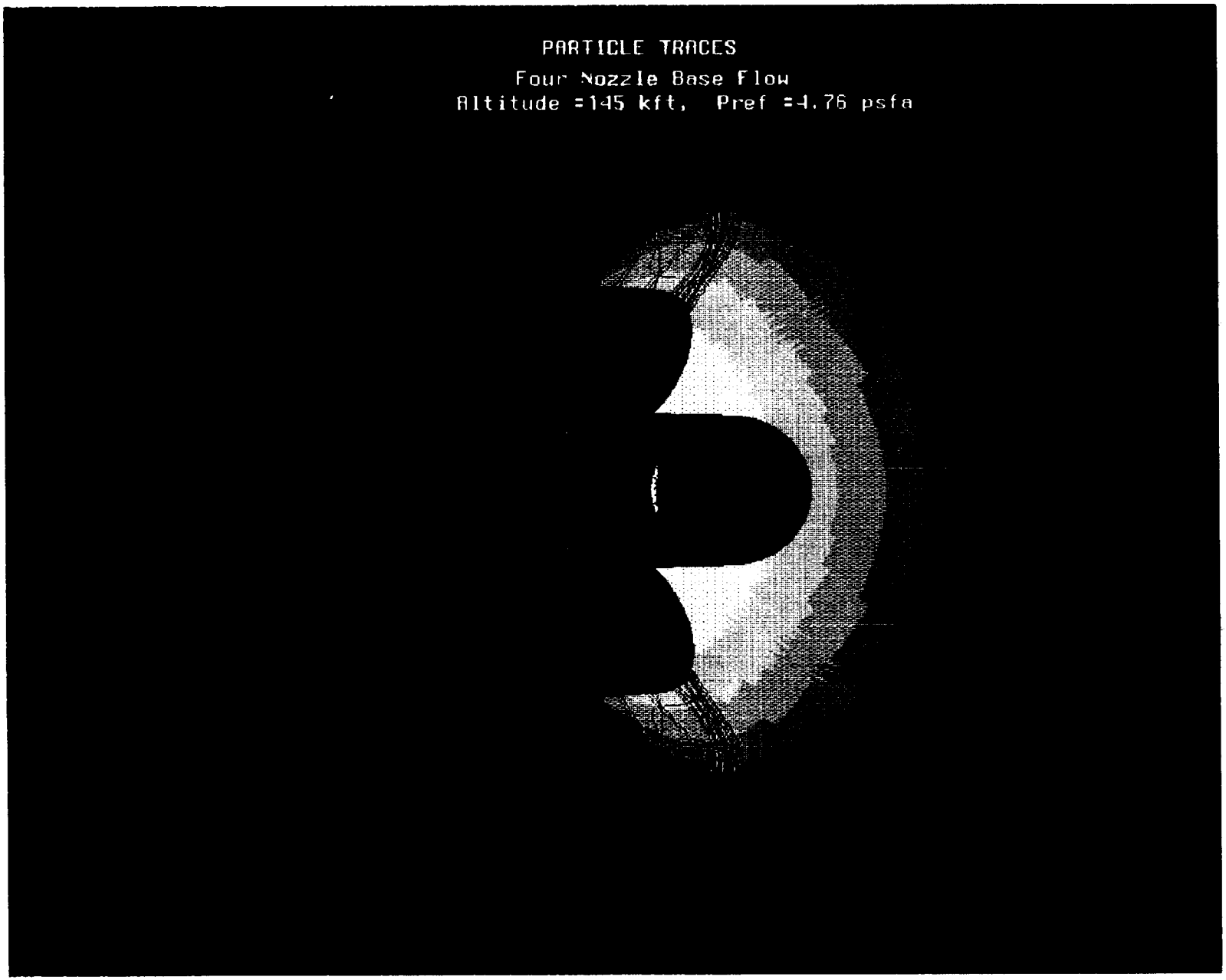

PARTICLE TRACES
Four Nozzle Base Flow
Altitude =145 kft. Pref =4.76 psfa

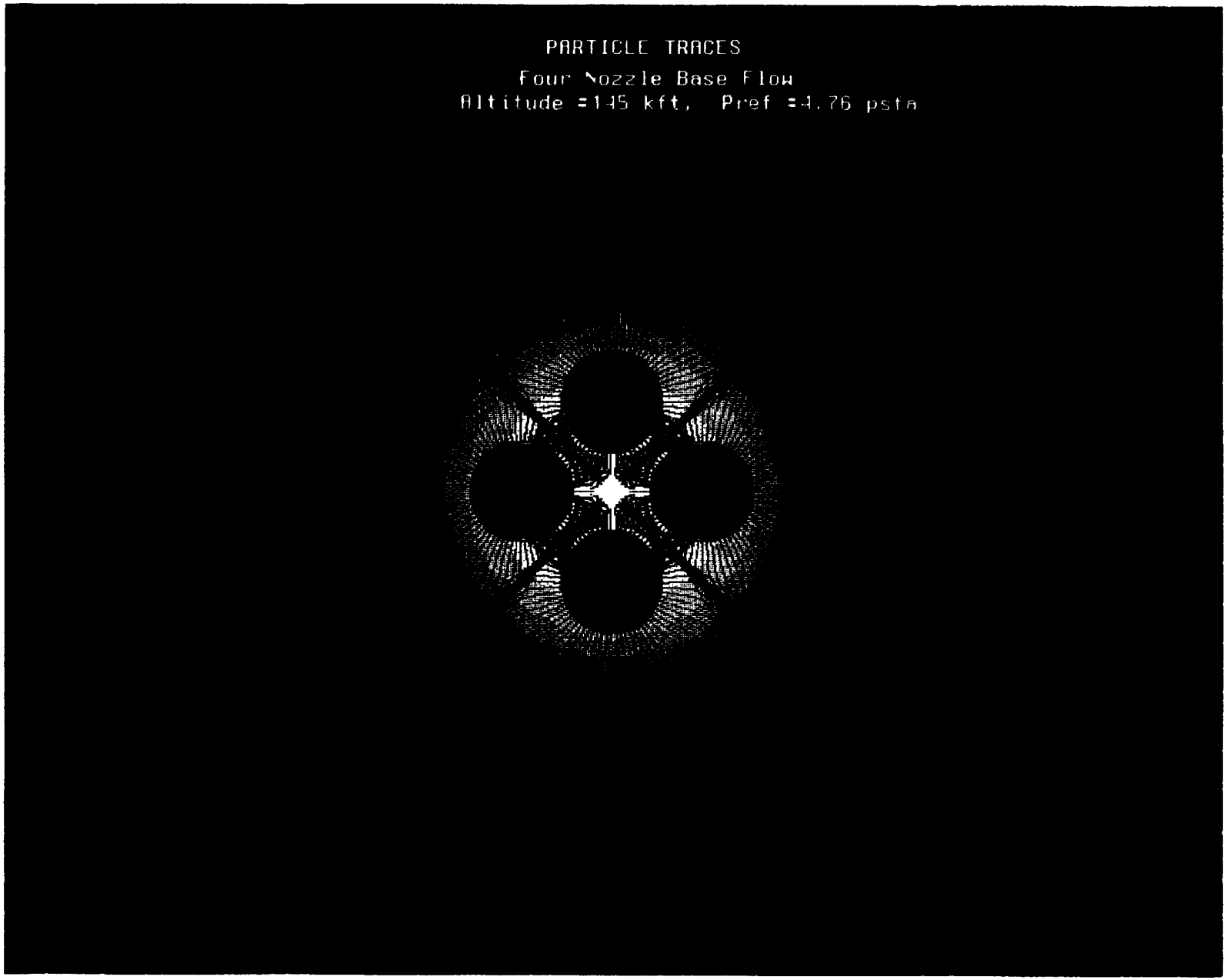


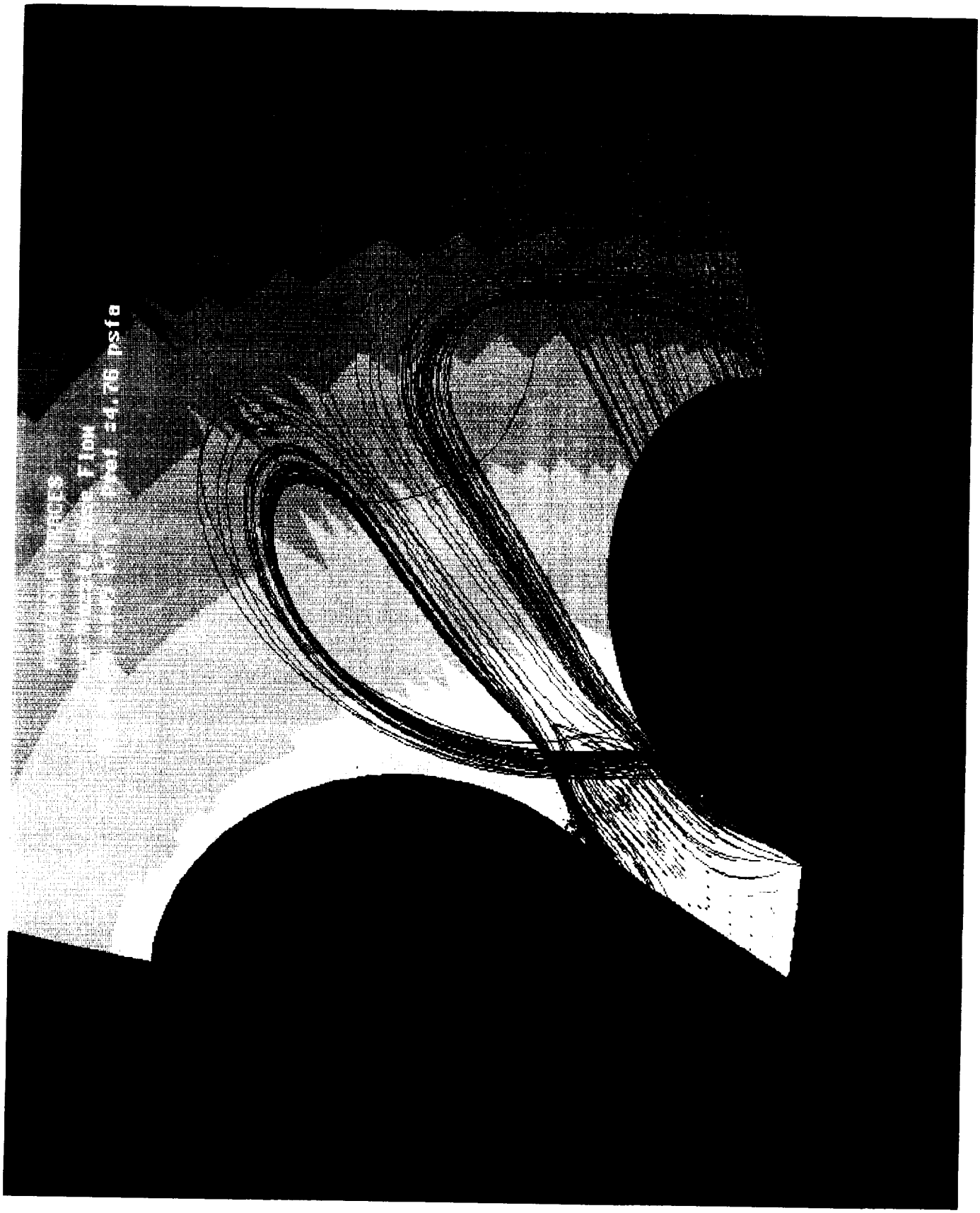
FOUR NOZZLE BASE PRESSURE

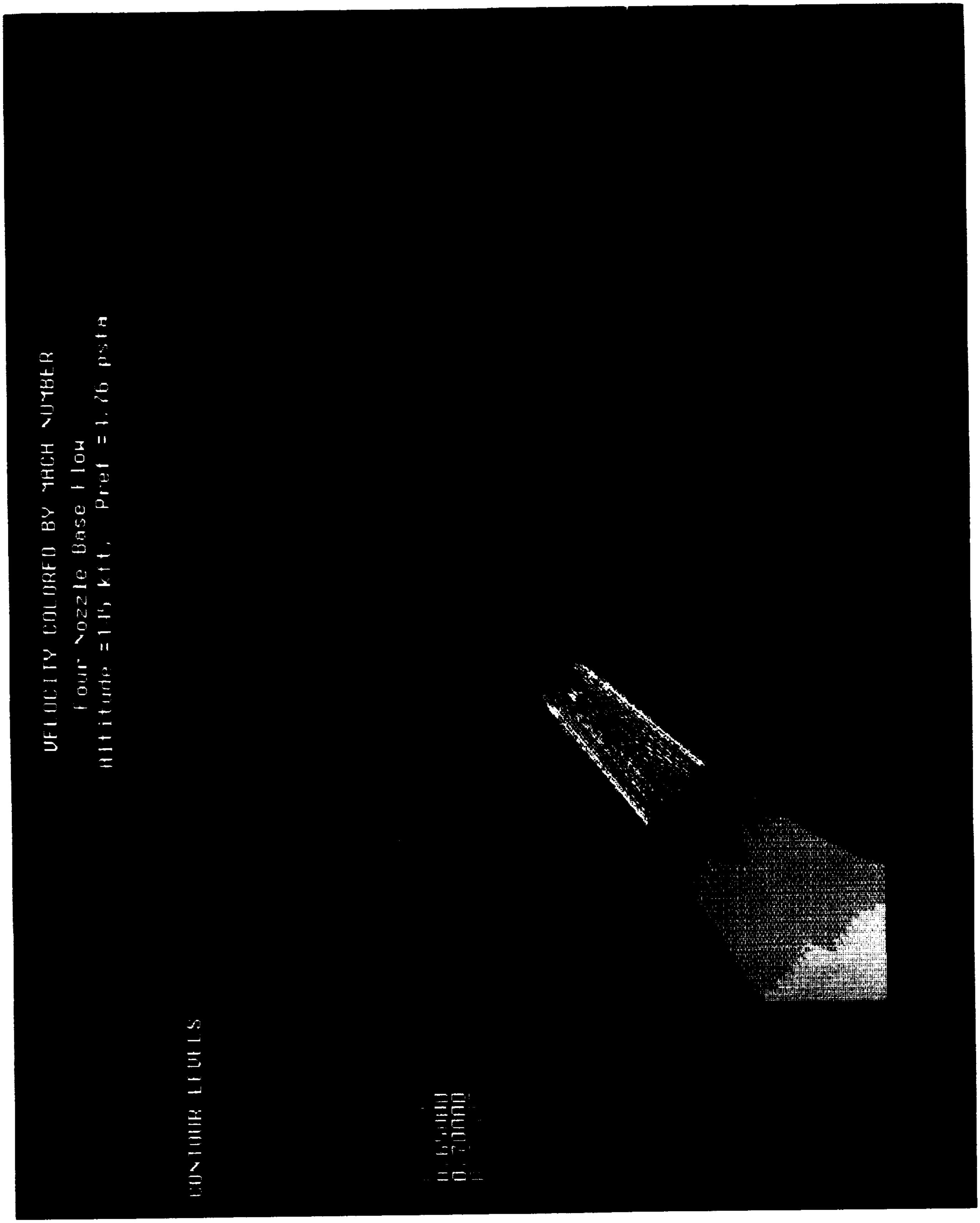


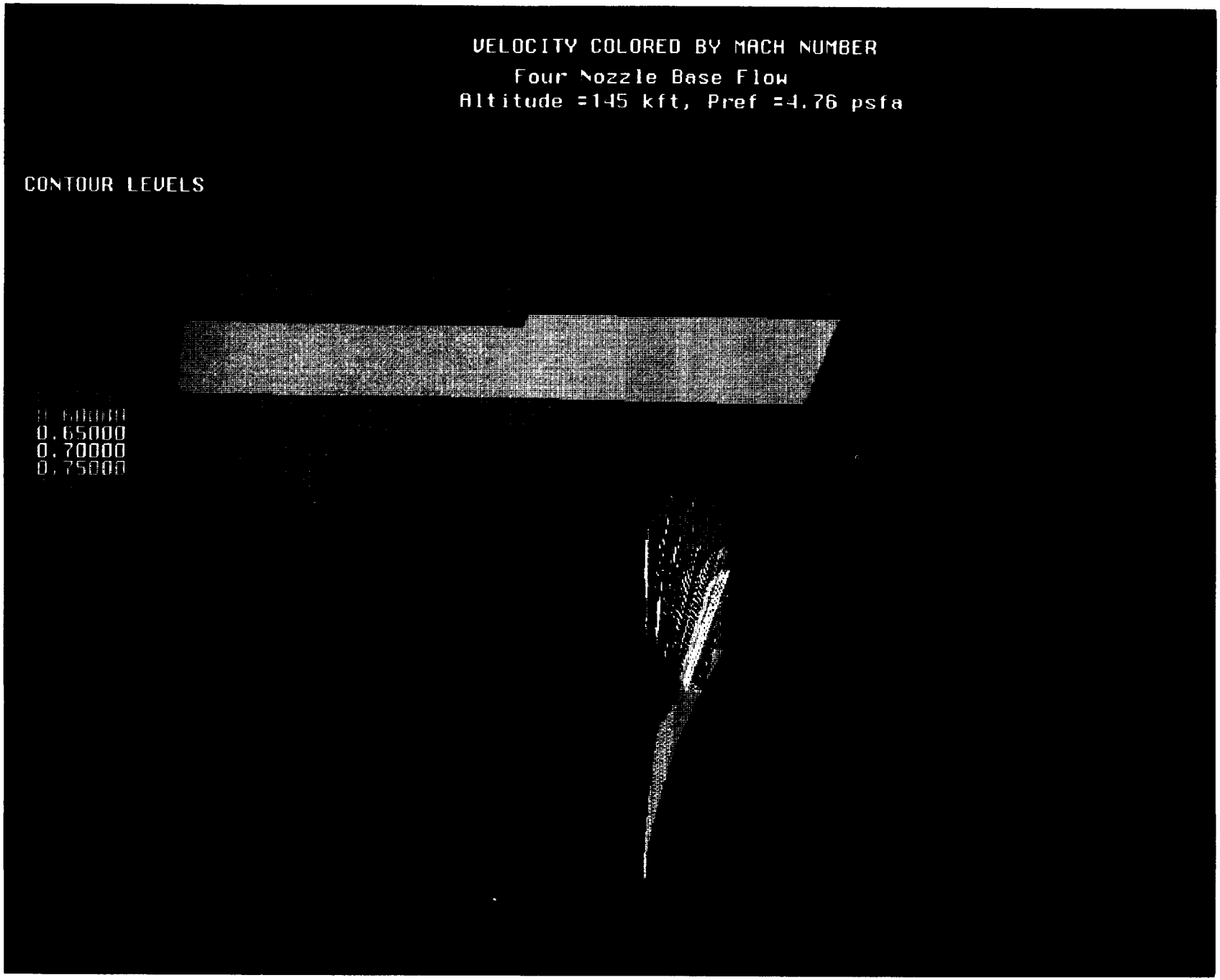

PARTICLE TRACES
Four Nozzle Base Flow
Altitude = 145 kft, Pref = 1.76 psfa


PARTICLE TRACES
Four Nozzle Base Flow
Altitude =145 kft, Pref =4.76 psfa


PARTICLE TRACES
Four Nozzle Base Flow
Altitude =145 kft, Pref =4.76 psia







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CONCLUSIONS

- BASE RECIRCULATION FLOW IN THE SIMULATION HAS THE SAME PATTERN AS THE EXPERIMENT
- THERE WAS AN EXCELLENT AGREEMENT WITH THE MAXIMUM PRESSURE AT THE CENTER OF THE BASE (3.3 X FREE-STREAM)
- SMALL DISAGREEMENT IN PRESSURE PROFILE ACROSS THE BASE BETWEEN NOZZLES REMAINS AFTER SEVERAL TRIAL VARIATIONS IN GRID AND TURBULENCE MODELING